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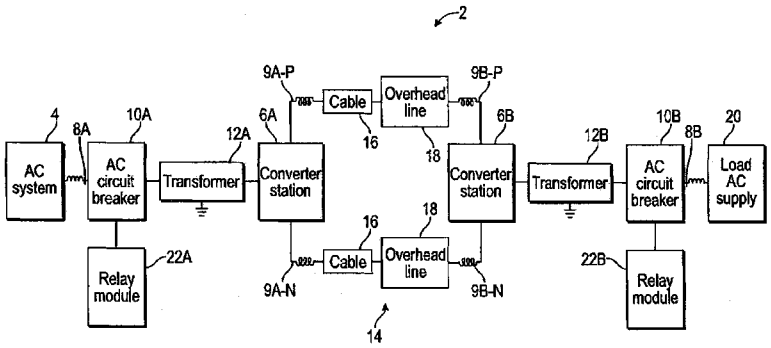


FIG. 1

(57) Abstract: Disclosed herein are methods, systems, and devices for identifying a location of a fault in a hybrid high voltage direct current (HVDC) transmission system having a ground or underground cable section and an overhead line section. Some methods comprise determining whether a characteristic voltage oscillation is present at a cable side terminal of the HVDC transmission system, and in response, determining that the fault is located in the overhead line section. Some methods comprise determining whether a characteristic current oscillation or a terminal current exceeding a peak current threshold is present at an overhead line side terminal, and in response, determining that the fault is located in the overhead line section. The methods can be communication-less, wherein the actions are based on local measurements and/or are performed locally to where the fault is located or detected.

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COMMUNICATION-LESS FAULT SECTION IDENTIFICATION FOR HYBRID HVDC TRANSMISSION SYSTEMS

CROSS-REFERENCE TO RELATED APPLICATIONS

[01] This application claims the benefit of U.S. Provisional Patent Application No. 62/166,869 filed May 27, 2015, which is incorporated by reference herein in its entirety.

FIELD

[02] This application pertains to hybrid high voltage direct current (HVDC) electric power transmission systems, and in particular, to systems and methods for communication-less fault section identification in hybrid HVDC transmission systems.

BACKGROUND

[03] A high voltage direct current (HVDC) electric power transmission system is a power transmission system that uses direct current for the bulk transmission of electrical power, typically over long distances. An HVDC transmission system that utilizes both underground/undersea cables and overhead transmission lines to transmit electrical power is here referred to as a hybrid HVDC transmission system. Hybrid HVDC transmission systems present a solution to transmit electricity in areas that have environmental constraints or permission issues.

[04] Modern HVDC power transmission systems use electronic converters to make the power conversions that are required for transmission. In particular, a first converter station (commonly referred to as the rectifier station) is used to convert generated AC power into high voltage DC power for transmission over long distances. At the destination end of the transmission system, a second converter station (commonly referred to as the inverter station) is used to convert the received high voltage DC power into AC power that is appropriate for customer use.

[05] One type of HVDC power transmission technology currently in use is known as line-commutated converter (LCC) HVDC power transmission. This type of system uses thyristors to construct the switching elements of the converters and commutation is carried out by the AC system voltage. Another, newer type of HVDC power transmission technology is known as voltage-sourced converter (VSC) HVDC power transmission. This type of system uses IGBTs (or similar power semiconductor devices) to construct the switching elements of the converters and offers certain benefits over LCC technology, such as the ability to control both real and reactive power flow. However, critical issues with VSC HVDC technology are currently preventing widespread deployment of the technology. In particular, all HVDC transmission systems regardless

of type require a fault handling system to isolate faults, diminish the fault current, and return the system to full power operation in a short period of time.

[06] A primary issue associated with VSC HVDC systems is that, in the event of a system fault, the energy stored in submodule capacitors of the system will quickly feed the system fault if not appropriately protected against. If a non-local communications channel were to be employed for purposes of implementing a fault protection/handling system, time delays would be introduced, which in turn would impact the speed of protection response. Associated with this communications delay, the capacitive energy has additional time to feed system faults.

SUMMARY

[07] Disclosed herein are methods, systems, and devices for identifying a location of a fault in a hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section. Some methods comprise determining whether a characteristic voltage oscillation is present at a cable side terminal of the HVDC transmission system, and in response, determining that the fault is located in the overhead line section. Some methods comprise determining whether a characteristic current oscillation or a terminal current exceeding a peak current threshold is present at an overhead line side terminal, and in response, determining that the fault is located in the overhead line section. The methods can be communication-less, wherein the actions are based on local measurements and/or are performed locally to where the fault is located or detected, without using communications channels to communicate between substations.

[08] Some methods further comprise reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the characteristic voltage oscillation is present at the cable side terminal.

[09] Some methods further comprise, responsive to determining that the characteristic voltage oscillation is not present at the cable side terminal and responsive to determining that a predetermined time period has expired, determining whether a voltage at the cable side terminal exceeds a buildup detection voltage threshold, responsive to determining that the voltage at the cable side terminal exceeds the buildup detection voltage threshold, determining that the fault is located in the overhead line section, and responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection voltage threshold, determining that the fault is located in the cable section.

[10] Some methods further comprise reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal exceeds the buildup detection voltage

threshold, and not reclosing the cable side circuit breaker of the HVDC transmission system and not commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection threshold.

[11] In some methods, determining whether a characteristic voltage oscillation is present comprises determining whether a voltage at the cable side terminal exceeds a predetermined oscillation detection voltage threshold. In some methods, the characteristic voltage oscillation comprises a signal having a frequency of about 10 Hz.

[12] Some methods further comprise determining that a cable side circuit breaker has been operated prior to determining whether a characteristic voltage oscillation is present.

[13] Also disclosed herein are relay modules for a hybrid high voltage direct current (HVDC) transmission systems having a cable section and an overhead line section. The relay modules include a control system that stores and is structured to execute a number of routines structured to carry out the methods disclosed herein, such as determining whether a characteristic voltage oscillation is present at a cable side terminal of the HVDC transmission system, and in response, determining that the fault is located in the overhead line section. The number of routines can be dependent on measurements local to the cable side terminal.

[14] The foregoing and other objects, features, and advantages of the disclosed technology will become more apparent from the following detailed description, which proceeds with reference to the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[15] FIG. 1 is a system diagram for an exemplary hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section.

[16] FIG. 2 is a schematic diagram of exemplary relay modules comprising computing device having a control system including a processor and a memory.

[17] FIG. 3 is a graph showing oscillation in voltage over time within an HVDC transmission system after a fault occurs.

[18] FIG. 4 is a graph showing oscillation in current over time within an HVDC transmission system after a fault occurs.

[19] FIG. 5 is a flow chart illustrating an exemplary method disclosed herein for determining whether to reclose a cable side AC circuit breaker and commence restart of the system.

[20] FIG. 6 is a flow chart illustrating an exemplary method disclosed herein for determining whether to reclose an overhead line side AC circuit breaker and commence restart of the system.

DETAILED DESCRIPTION

[21] As used herein, the singular form of "a", "an", and "the" include plural references unless the context clearly dictates otherwise.

[22] As used herein, the statement that two or more parts or components are "coupled" shall mean that the parts are joined or operate together either directly or indirectly, e.g., through one or more intermediate parts or components.

[23] As used herein, "directly coupled" means that two elements are directly in contact with each other.

[24] As used herein, the term "number" shall mean one or an integer greater than one (i.e., a plurality).

[25] As used herein, the term "terminal" shall mean a point of electrical connection.

[26] As used herein, the term "cable side terminal" shall mean the point of electrical connection between the cable and adjacent electronic converter.

[27] As used herein, the term "overhead line side terminal" shall mean the point of electrical connection between the overhead line and adjacent electronic converter.

[28] As used herein, the terms "component" and "system" are intended to refer to a computer related entity, either hardware, a combination of hardware and software, software, or software in execution. For example, a component can be, but is not limited to being, a process running on a processor, a processor, an object, an executable, a thread of execution, a program, and/or a computer. By way of illustration, both an application running on a server and the server can be a component. One or more components can reside within a process and/or thread of execution, and a component can be localized on one computer and/or distributed between two or more computers.

[29] As used herein, the term "and/or" used between the last two of a list of elements means any one or more of the listed elements. For example, the phrase "A, B, and/or C" means "A," "B," "C," "A and B," "A and C," "B and C" or "A, B and C."

[30] Directional phrases used herein, such as, for example and without limitation, top, bottom, left, right, upper, lower, front, back, and derivatives thereof, relate to the orientation of the elements shown in the drawings and are not limiting upon the claims unless expressly recited therein.

[31] Although the operations of some of the disclosed methods are described in a particular, sequential order for convenient presentation, it should be understood that this manner of description encompasses rearrangement, unless a particular ordering is required by specific language. For example, operations described sequentially may in some cases be rearranged or performed concurrently. Moreover, for the sake of simplicity, the attached figures may not show the various ways in which the disclosed methods can be used in conjunction with other methods.

[32] The disclosed technology is described herein, for purposes of explanation, in connection with numerous specific exemplary details in order to provide a thorough understanding of the subject matter. It will be evident, however, that the present novel technology can be practiced without these specific details without departing from the spirit and scope of this innovation.

[33] FIG. 1 is a schematic diagram of a hybrid HVDC transmission system 2 according to an exemplary embodiment of the disclosed concept. Hybrid HVDC transmission system 2 includes an AC system 4 which generates AC power using any suitable method. The AC power generated by AC system 4 is provided to a first converter station 6A through a first terminal 8A, a first AC circuit breaker 10A, and a step up transformer 12A. First converter station 6A is structured to convert the AC power it receives from transformer 12A to DC power for subsequent transmission as described herein. Hybrid HVDC transmission system 2 also includes an HVDC line 14 which connects first converter station 6A to a second converter station 6B. In the illustrated exemplary embodiment, HVDC line 14 includes a cable section 16 (comprising underground and/or undersea cables) which is connected to an overhead line section 18.

[34] As seen in FIG. 1, in the illustrated exemplary embodiment, cable section 16 and overhead line section 18 are adjacent to and directly connected to one another, with cable section 16 being directly connected to the first converter station 6A at cable side terminal 9A (including positive (9A-P) and negative (9A-N) connections) and overhead line section 18 being directly connected to the second converter station 6B at overhead line side terminal 9B (including positive (9B-P) and negative (9B-N) connections). It will be understood, however, that this configuration is exemplary only and that the positions of cable section 16 and overhead line section 18 may be switched within the scope of the disclosed concept. Second converter station 6B is structured to convert the DC power it receives through HVDC line 14 back to AC power. That AC power is provided to a step down transformer 12B which in turn provides the stepped down AC power to a local AC supply 20 (for feeding a number of loads) through a second AC circuit breaker 10B and a second terminal 8B.

[35] In the exemplary embodiment, hybrid HVDC transmission system 2 is a VSC HVDC power transmission system, and thus both first converter station 6A and second converter station 6B comprise voltage sourced converters employing IGBTs or similar devices to form the switching elements thereof. Any suitable VSC converter topology may be employed to implement first converter station 6A and second converter station 6 B, such as, without limitation, the modular multilevel converter (MMC) topology that is well known in the art.

[36] In addition, as seen in FIG. 1, HVDC transmission system 2 further includes a first relay module 22A that is operatively coupled to first AC circuit breaker 10A, and a second relay module

22B that is operatively coupled to second AC circuit breaker 10B. As is known in the art, a relay module is a protective device that measures the voltage and/or current at a given location and sends signals to an AC circuit breaker to open and close the AC circuit breaker as appropriate based on the voltage and/or current measurements. Thus, in the illustrated exemplary embodiment, first relay module 22A is structured to measure the voltage and current at terminal 9A and send signals to first AC circuit breaker 10A to open and close first AC circuit breaker 10A as appropriate. Similarly, second relay module 22B is structured to measure the voltage and current at terminal 9B and send signals to second AC circuit breaker 10B to open and close second AC circuit breaker 10B as appropriate.

[37] FIG. 2 is a schematic diagram of first and second relay modules 22A, 22B according to one non-limiting exemplary embodiment. In the exemplary embodiment, each relay module 22A, 22B comprises a computing device having a control system including a processor 24 and a memory 26. Processor 24 may be, for example and without limitation, a microprocessor (μP), a microcontroller, or some other suitable processing device, that interfaces with memory 26. Memory 26 can be any one or more of a variety of types of internal and/or external storage media such as, without limitation, RAM, ROM, EPROM(s), EEPROM(s), FLASH, and the like that provide a storage register, i.e., a machine readable medium, for data storage such as in the fashion of an internal storage area of a computer, and can be volatile memory or nonvolatile memory. Memory 26 has stored therein a number of routines that are executable by processor 24. One or more of the routines implement (by way of computer/processor executable instructions) at least one embodiment of the methods discussed in greater detail below for identifying faults sections in HVDC transmission system 2 and taking appropriate action based thereon.

[38] Furthermore, as seen in FIG. 2, each relay module 22A, 22B further includes a number of voltage sensors 28 (e.g., voltage transformers) for measuring the voltage at terminals 9A, 9B, respectively, and a number of current sensors 30 (e.g. current transformers) for measuring the current at terminals 9A, 9B, respectively. In the exemplary embodiment, the voltage sensors 28 and current sensors 30 make respective voltage and current measurements on the line side of the associated converter station 6A, 6B. The analog signals generated by the number of voltage sensors 28 and the number of current sensors 30 are fed to an analog-to-digital converter 32 which converts those signals into digital form and provides them to processor 24 for use as described herein.

[39] In operation, first relay module 22A monitors the voltage and current at terminal 9A for conditions indicative of a fault in hybrid HVDC transmission system 2, and similarly second relay module 22B monitors the voltage and current at terminal 9B for conditions indicative of a fault in hybrid HVDC transmission system 2. When first and second relay modules 22A, 22B determine

that a fault has occurred, each will generate and transmit a signal for opening the associated AC circuit breaker 10A, 10B in order to protect hybrid HVDC transmission system 2 from the fault. Thus, in HVDC transmission system 2, it is important for fault current to be extinguished quickly (i.e., decayed to the zero) so that the converter fault withstand rating of each converter station 6A, 6B is not surpassed and so that a system restart sequence, including re-closing of AC circuit breakers 10A, 10B followed by voltage stabilization and restart of power flow, can commence as soon as possible.

[40] In this regard, it is important to note that if the fault occurs in cable section 16, the fault is considered to be permanent and a re-closure/restart procedure cannot start until the cable is repaired or replaced. Conversely, if the fault occurs in overhead line section 18, the fault is considered to be temporary the re-closure/restart procedure can start immediately. Thus, it is desirable to identify the faulted section of HVDC line 14 in order to know whether or not to attempt an immediate reclose of AC circuit breakers 10A, 10B and system restart. Again, in the case of a non-permanent fault on HVDC line 14, an immediate attempt to reclose AC circuit breakers 10A, 10B is desirable for system restart. In the case of a permanent fault, likely to occur within cable section 16 since all cable faults can be assumed to be permanent, reclosing the AC circuit breakers 10A, 10B and restarting the system is not possible until the faulty cable is repaired or replaced. An attempt to reclose during a permanent fault will be unsuccessful, and is known as a false reclose. A false reclose will only result in feeding the fault and can potentially damage system components.

[41] Some transmission systems implement protective relay coordination for system fault handling/protection using a long distance communication channel between the converter stations. This is primarily due to the fact that most transmission relay protection is in the form of line current differential protection which requires a communications channel inherent to the relay function. However, communications in fault handling/protection inherently slow down the process of restarting the transmission system after a fault event. Long distance communications are also expensive and can often be unreliable. For the purpose of faster fault isolation and faster system restart, it is therefore desirable to design a protection coordination scheme that does not utilize long distance communications channel between converter stations, but rather utilizes local measurements, local communications, local determinations, and local responsive actions. These actions can all occur at or near a single converter station or substation at or near where the fault occurs, such as at the junctions between lines and the substation, including the substation and the DC line terminations. This can save time and reduce energy loss and energy shortages/blackouts compared to systems that employ long distance communications for system fault detection/response.

[42] Hence, as described in detail herein, the disclosed concept presents a novel solution to this problem by employing a methodology that can quickly determine the faulted section within HVDC line 14 without the aid of telecommunication. In particular, the methodology of the disclosed concept is able to determine whether a given DC fault is located in cable section 16 or overhead line section 18 without using a communications channel. Thereafter, once that determination is made, system restart can be attempted for faults that are identified to have occurred in overhead line section 18 (temporary faults), while for faults identified in cable section 16 (permanent faults), hybrid HVDC transmission system 2 will remain in shutdown mode until the faulty cable is repaired or replaced.

[43] In the case of certain types of faults within hybrid HVDC transmission system 2 and post opening of AC circuit breakers 10A, 10B, a distinct signal characteristic exists within hybrid HVDC transmission system 2. In particular, that distinct signal characteristic is, in the non-limiting exemplary embodiment, in the form of a low frequency oscillation in the range of about 10 Hz (which frequency, however, may vary based on the particulars of the implementation), shown in exemplary form in FIG. 3 (oscillation in voltage) and FIG. 4 (oscillation in current), and is present only in the case of a pole-to-ground (also referred to as a line-to-ground) fault in overhead line section 18. More specifically, the present inventors have determined that, for pole-to-ground faults in overhead line section 18, such an oscillation exists in voltage form only at the terminal closest to cable section 16 (e.g., terminal 9A in the illustrated example) and that such an oscillation simultaneously exists in current form only at the terminal closest to overhead line section 18 (terminal 9B in the illustrated example). Furthermore, the characteristic oscillation signal is not present in the case of pole-to-pole faults in overhead line section 18 or in pole-to-ground or pole-to-pole faults in cable section 16. Thus, the detection of the presence of such an oscillating signal may be used as an indicator of a pole-to-ground fault in overhead line section 18 and thus an indicator that a system reclose/restart can commence as soon as the fault current has decayed completely.

[44] However, as noted above, it is also desirable to commence a system reclose/restart as soon as the fault current has decayed completely in the case of pole-to pole faults in overhead line section 18. Thus, the detection of the characteristic oscillating signal as described herein is not enough to classify all types of faults that permit immediate (i.e., as the fault current has decayed completely) commencement of system restart. In other words, whenever there is a pole-to-pole fault in overhead line section 18, there is a challenge to identifying that type of fault because the characteristic oscillating signal is not present. However, according to a further aspect of the disclosed concept, the inventors have determined that a high current will be observed on the terminal (terminal 9A or terminal 9B) that is nearest the faulted section. Thus, in the case of a fault

that is not a pole-to-ground fault on overhead line section 18, detection of such a high current may be used to further classify/identify the location of the fault as being in either overhead line section 18 or cable section 16. In particular, in the exemplary embodiment shown in FIG. 1, if the high current is observed in terminal 9A, it is known that the fault is a pole-to-pole or a pole-to-ground fault in cable section 16, and if the high current is observed at terminal 9B, it is known that the fault is a pole-to-pole fault in overhead line section 18.

[45] Thus, in cases where a pole-to-ground fault in overhead line 18 is detected based upon detection of the characteristic oscillating signal or where a pole-to-pole fault in overhead line 18 is detected based upon detection of the current threshold being surpassed at the terminal closest to overhead line section 18 (terminal 9B in the present example), relay module 22B may send a signal to AC circuit breaker 10B to reclose. However, as will be appreciated, in either of the two cases just described, it is also necessary to cause AC circuit breaker 10A to reclose so that the restart procedure may proceed. A challenge is presented as to how to accomplish such a reclosing operation at the terminal nearest cable section 16 (terminal 9A in the present example) without the aid of any telecommunications. According to a further aspect of the disclosed concept, this challenge is met using the voltage buildup that will occur at the terminal nearest cable section 16 (terminal 9A in the present example) as a result of successful reclose of the AC circuit breaker closest to overhead line section 18 (AC circuit breaker 10B in the present example). More specifically, voltage buildup at the terminal nearest cable section 16 (terminal 9A in the present example) is monitored and relay module 22A will initiate a reclosing operation by sending a signal to AC circuit breaker 10A when a certain predetermined voltage threshold is determined to have been surpassed. As will be appreciated, this will successfully reclose the cable side circuit breaker without necessitating a communications channel in hybrid HVDC transmission system 2. It is important to note, however, that when a pole-to-pole fault occurs in cable section 16, a peak current but not a peak voltage will exist at terminal 9A, but because relay module 22A is only making a voltage threshold detection to detect oscillation, no attempt to reclose will occur.

[46] FIG. 5 is a flowchart showing a method of fault section identification that may be implemented in the cable side relay module 22A according to an aspect of the disclosed concept. The method shown in FIG. 5 may be implemented in one or more routines stored in the memory 26 of relay module 22A and executable by the processor 24 of relay module 22A. The method begins at step 40, wherein a determination is made as to whether cable side AC circuit breaker 10A has been operated (i.e., has been opened). If the answer is no, then the method returns to step 40. If, however, the answer at step 40 is yes, then the method proceeds to step 42. At step 42, a determination is made as to whether the characteristic oscillation described herein has been

detected at cable side terminal 9A by relay module 22A. In the exemplary embodiment, such an oscillation is detected by relay module 22A by monitoring the voltage at terminal 9A using a voltage sensor 28 and determining whether that voltage has exceeded a predetermined oscillation detection voltage threshold. In the exemplary embodiment, this threshold is ultimately determined and set during a sensitivity analysis that is provided as a part of a specific installation of HVDC transmission system 2. It will be understood, however, that other methods for detecting the characteristic oscillating signal, such as looking for a signal with the characteristic frequency, are contemplated within the scope of the disclosed concept. If the answer at step 42 is yes, meaning that the characteristic oscillation has been detected, thereby indicating that a pole-to-ground fault in overhead line section 18 has occurred, then, at step 44, relay module 22A takes steps to reclose cable side AC circuit breaker 10A and commence a restart procedure.

[47] If the answer at step 42 is no, meaning that the characteristic oscillation has not been detected (i.e., no pole-to-ground fault in overhead line section 18 detected), then the method proceeds to step 46. At step 46, a determination is made as to whether a predetermined oscillation detection time period has expired. If the answer is no, then the method returns to step 42. However, if the answer at step 46 is yes, then the method proceeds to step 48. At step 48, a determination is made as to whether the voltage at terminal 9A has exceeded a predetermined buildup detect threshold (caused by the reclosure of AC circuit breaker 10B as described elsewhere herein). If the answer at step 48 is yes (which is indicative of a pole-to-pole fault in overhead line section 18 is described herein), then the method proceeds to step 44 and the above-described reclose and restart procedure is initiated. If the answer at step 48 is no, then at step 50 a determination is made as to whether a predetermined buildup detection time period has expired. If the answer is no, then the method returns to step 48. If the answer at step 50 is yes, then the method proceeds to step 52, wherein relay module 22A determines that the AC circuit breaker 10A should not be reclosed and that a restart procedure should not be commenced because the fault is a fault occurring in cable section 16. As described herein, HVDC transmission system 2 will stay in such a shutdown mode until the cable fault has been repaired or replaced.

[48] In the method of FIG. 5, the buildup detection voltage threshold and the oscillation detection voltage threshold may be the same value or may be different, depending upon the particulars of the installation.

[49] FIG. 6 is a flowchart showing a method of fault section identification that may be implemented in the overhead line side relay module 22B according to another aspect of the disclosed concept. The method shown in FIG. 6 may be implemented in one or more routines stored in the memory 26 of relay module 22B and executable by the processor 24 of relay module

22B. The method begins at step 60, wherein a determination is made as to whether overhead line side AC circuit breaker 10B has been operated (i.e., has been opened). If the answer is no, then the method returns to step 60. If, however, the answer at step 60 is yes, then the method proceeds to step 62. At step 62, a determination is made as to whether: (i) the characteristic oscillation has been detected at overhead line side terminal 9B (which is indicative of a pole-to-ground fault in overhead line section 18), or (ii) the current at terminal 8 as measured by a current sensor 30 is greater than a predetermined peak current threshold (which is indicative of a pole-to-pole fault in overhead line section 18). In the exemplary embodiment, such an oscillation is detected by relay module 22B by monitoring the current at terminal 9B using a current sensor 28 and determining whether that current has exceeded a predetermined oscillation detection current threshold. In the exemplary embodiment, this threshold is ultimately determined and set during a sensitivity analysis that is provided as a part of a specific installation of HVDC transmission system 2. It will be understood, however, that other methods for detecting the characteristic oscillating signal, such as looking for a signal with the characteristic frequency, are contemplated within the scope of the disclosed concept. If the answer at step 62 is yes, meaning that the fault is within overhead line section 18, then the method proceeds to step 64 wherein relay module 22B takes steps to reclose overhead line side AC circuit breaker 10B and commence a restart procedure. If the answer at step 62 is no, then the method proceeds to step 66, wherein a determination is made as to whether a predetermined detection time period has expired. If the answer at step 66 is no, the method returns to step 62. If, however, the answer at step 66 is yes, that is indicative of a pole-to-ground or a pole-to-pole fault in cable section 16, and the method proceeds to step 68. At step 68, relay module 22B determines that the AC circuit breaker 10B should not be reclosed and that a restart procedure should not be commenced because the fault is a fault occurring in cable section 16. As described herein, since AC circuit breaker 10B has not been reclosed, voltage buildup will not occur at terminal 9A and as a result AC circuit breaker 10 A will not be re-closed. Instead, HVDC transmission system 2 will stay in such a shutdown mode until the cable fault has been repaired or replaced.

[50] Thus, the disclosed concept provides a novel methodology for quickly determining the faulted section within HVDC line 14 without the aid of telecommunication so that reclosure and restart can occur immediately where appropriate and so that reclosure and restart will be prevented where appropriate until the fault is cleared.

[51] In the claims, any reference signs placed between parentheses shall not be construed as limiting the claim. The word “comprising” or “including” does not exclude the presence of elements or steps other than those listed in a claim. In a device claim enumerating several means, several of these means may be embodied by one and the same item of hardware. The word “a” or

"an" preceding an element does not exclude the presence of a plurality of such elements. In any device claim enumerating several means, several of these means may be embodied by one and the same item of hardware. The mere fact that certain elements are recited in mutually different dependent claims does not indicate that these elements cannot be used in combination.

[52] Although the disclosed technology has been described in detail for the purpose of illustration based on certain embodiments, it is to be understood that the innovative technology disclosed herein is not limited to the particularly disclosed embodiments, but is intended to cover modifications and equivalent arrangements that are within the spirit and scope of the appended claims. For example, it is to be understood that the disclosure contemplates that, to the extent possible, one or more features of any embodiment can be combined with one or more features of any other embodiment.

CLAIMS:

1. A method of identifying a location of a fault in a hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section, the method comprising:

determining whether a characteristic voltage oscillation is present at a cable side terminal of the HVDC transmission system; and

responsive to determining that the characteristic voltage oscillation is present at the cable side terminal, determining that the fault is located in the overhead line section.

2. The method according to claim 1, wherein the method is performed locally without using a long distance communication channel between converter stations.

3. The method according to claim 1 or claim 2, further comprising reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the characteristic voltage oscillation is present at the cable side terminal.

4. A method according to any one of claims 1-3, further comprising, responsive to determining that the characteristic voltage oscillation is not present at the cable side terminal and responsive to determining that a predetermined time period has expired, determining whether a voltage at the cable side terminal exceeds a buildup detection voltage threshold, responsive to determining that the voltage at the cable side terminal exceeds the buildup detection voltage threshold, determining that the fault is located in the overhead line section, and responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection voltage threshold, determining that the fault is located in the cable section.

5. The method according to claim 4, further comprising reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal exceeds the buildup detection voltage threshold, and not reclosing the cable side circuit breaker of the HVDC transmission system and not commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection threshold.

6. The method according to any one of claims 1-5, wherein the determining whether a characteristic voltage oscillation is present comprises determining whether a voltage at the cable side terminal exceeds a predetermined oscillation detection voltage threshold.

7. The method according to any one of claims 1-6, wherein the characteristic voltage oscillation comprises a signal having a frequency of about 10 Hz.

8. The method according to any one of claims 1-7, further comprising determining that a cable side circuit breaker has been operated prior to determining whether a characteristic voltage oscillation is present.

9. A relay module for a hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section, comprising:

a control system, wherein the control system stores and is structured to execute a number of routines, the number of routines being structured to:

determine whether a characteristic voltage oscillation is present at a cable side terminal of the HVDC transmission system; and

responsive to determining that the characteristic voltage oscillation is present at the cable side terminal, determine that the fault is located in the overhead line section.

10. The relay module according to claim 9, wherein the number of routines are dependent on measurements local to the cable side terminal.

11. The relay module according to claim 9 or claim 10, wherein the routines are further structured to generate one or more signals for reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the characteristic voltage oscillation is present at the cable side terminal.

12. A relay module according to any one of claims 9-11, wherein the routines are further structured to, responsive to determining that the characteristic voltage oscillation is not present at the cable side terminal and responsive to determining that a predetermined time period has expired, determine whether a voltage at the cable side terminal exceeds a buildup detection voltage threshold, responsive to determining that the voltage at the cable side terminal exceeds the buildup

detection voltage threshold, determine that the fault is located in the overhead line section, and responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection voltage threshold, determine that the fault is located in the cable section.

13. The relay module according to claim 12, wherein the routines are further structured to generate one or more signals for reclosing a cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal exceeds the buildup detection voltage threshold, and wherein the relay module is structured to not take any action for reclosing the cable side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the voltage at the cable side terminal does not exceed the buildup detection threshold.

14. The relay module according to any one of claims 9-13, wherein the routines are structured to determine whether a characteristic voltage oscillation is present by receiving a voltage value representing a voltage at the cable side terminal and determining whether the voltage value exceeds a predetermined oscillation detection voltage threshold.

15. The relay module according to any one of claims 9-14, wherein the characteristic voltage oscillation comprises a signal having a frequency of about 10 Hz.

16. The relay module according to any one of claims 9-15, wherein the routines are further structured to determine whether a cable side circuit breaker has been operated prior to determining whether a characteristic voltage oscillation is present.

17. A non-transitory computer readable medium storing one or more programs, including instructions, which when executed by a computer, causes the computer to perform the method of any one of claims 1-8.

18. A method of identifying a location of a fault in a hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section, comprising:

determining whether (i) a characteristic current oscillation or (ii) a terminal current exceeding a peak current threshold is present at an overhead line side terminal of the HVDC transmission system; and

responsive to determining that either the characteristic current oscillation or the terminal current exceeding the peak current threshold is present at the overhead line side terminal, determining that the fault is located in the overhead line section.

19. The method according to claim 18, wherein the method is performed locally to the overhead line side terminal without long distance communications.

20. The method according to claim 18 or claim 19, further comprising reclosing an overhead line side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the characteristic current oscillation or the terminal current exceeding the peak current threshold is present at the overhead line side terminal.

21. The method according to any one of claims 18-20, wherein the determining whether a characteristic current oscillation is present comprises determining whether a current at the overhead line side terminal exceeds a predetermined oscillation detection current threshold.

22. The method according to any one of claims 18-21, wherein the characteristic current oscillation comprises a signal having a frequency of about 10 Hz.

23. The method according to any one of claims 18-22, further comprising determining that an overhead line side circuit breaker has been operated prior to determining whether a characteristic current oscillation is present.

24. The method according to any one of claims 18-23, further comprising determining that the fault is located in the cable section responsive to determining that neither the characteristic current oscillation nor the terminal current exceeding the peak current threshold is present at the overhead line side terminal for at least a certain time period following a determination that overhead line side circuit breaker has been operated.

25. A relay module for a hybrid high voltage direct current (HVDC) transmission system having a cable section and an overhead line section, comprising:

a control system, wherein the control system stores and is structured to execute a number of routines, the number of routines being structured to:

determined whether (i) a characteristic current oscillation or (ii) a terminal current exceeding a peak current threshold is present at an overhead line side terminal of the HVDC transmission system; and

responsive to determining that either the characteristic current oscillation or the terminal current exceeding the peak current threshold is present at the overhead line side terminal, determine that the fault is located in the overhead line section.

26. The relay module according to claim 25, wherein the number of routines are dependent on measurements local to the overhead line side terminal.

27. The relay module according to claim 25 or claim 26, wherein the routines are further structured to generate one or more signals for reclosing an overhead line side circuit breaker of the HVDC transmission system and commencing a restart of the HVDC transmission system responsive to determining that the characteristic current oscillation or the terminal current exceeding the peak current threshold is present at the overhead line side terminal.

28. The relay module according to any one of claims 25-27, wherein routines are structured to determine whether a characteristic current oscillation is present comprises by determining whether a current at the overhead line side terminal exceeds a predetermined oscillation detection current threshold.

29. The relay module according to any one of claims 25-28, wherein the characteristic current oscillation comprises a signal having a frequency of about 10 Hz.

30. The relay module according to any one of claims 25-29, wherein the routines are further structured to determine that an overhead line side circuit breaker has been operated prior to determining whether a characteristic current oscillation is present.

31. The relay module according to claim 30, wherein the routines are further structured to determine that the fault is located in the cable section responsive to determining that neither the characteristic current oscillation nor the terminal current exceeding the peak current threshold is present at the overhead line side terminal for at least a certain time period following a determination that overhead line side circuit breaker has been operated.

32. A non-transitory computer readable medium storing one or more programs, including instructions, which when executed by a computer, causes the computer to perform the method of any one of claims 18-24.

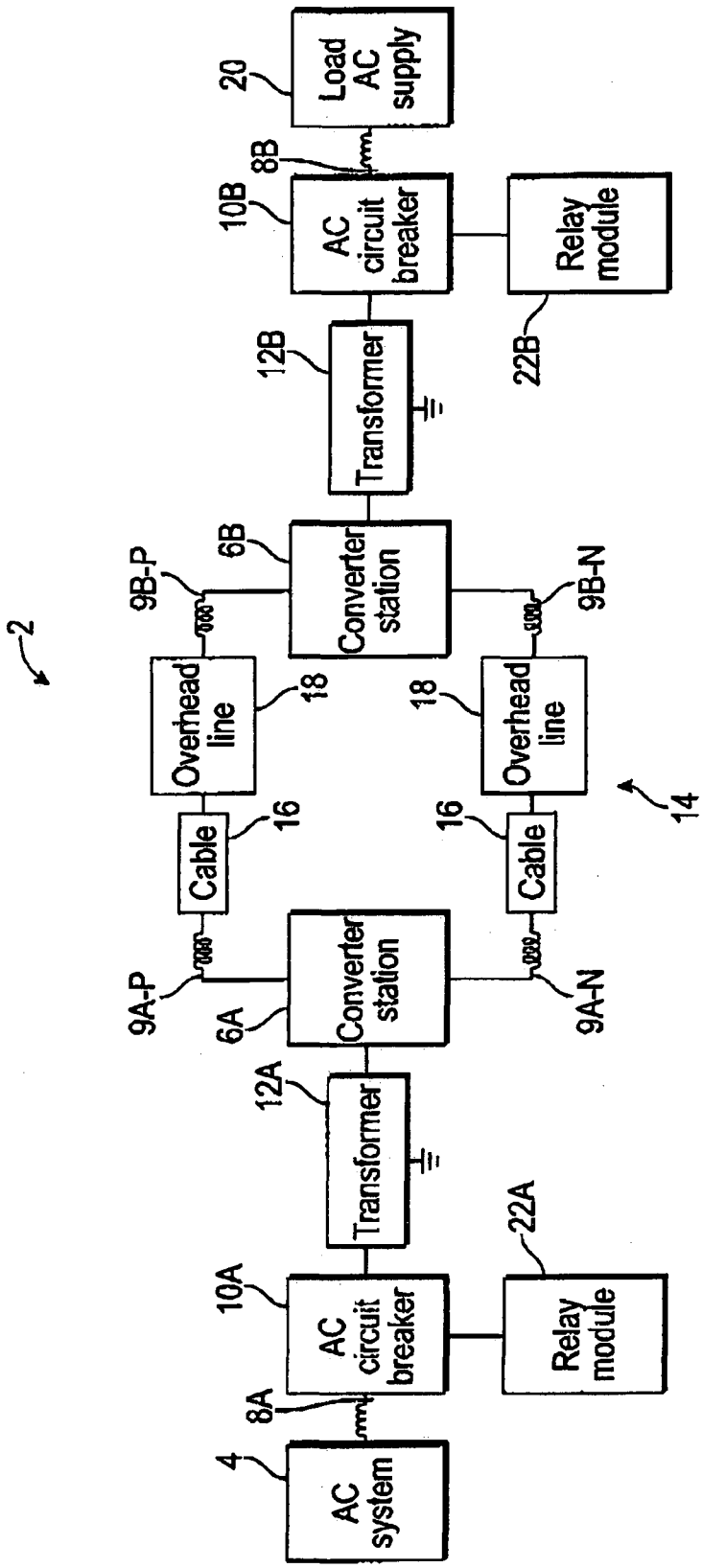

2
AC system
4
8A
AC circuit breaker
10A
Relay module
22A
Transformer
12A
Converter station
6A
9A-P
9A-N
Cable
16
Overhead line
18
Converter station
6B
9B-P
9B-N
Transformer
12B
AC circuit breaker
10B
8B
Relay module
22B
Load AC supply
20
14

FIG. 1

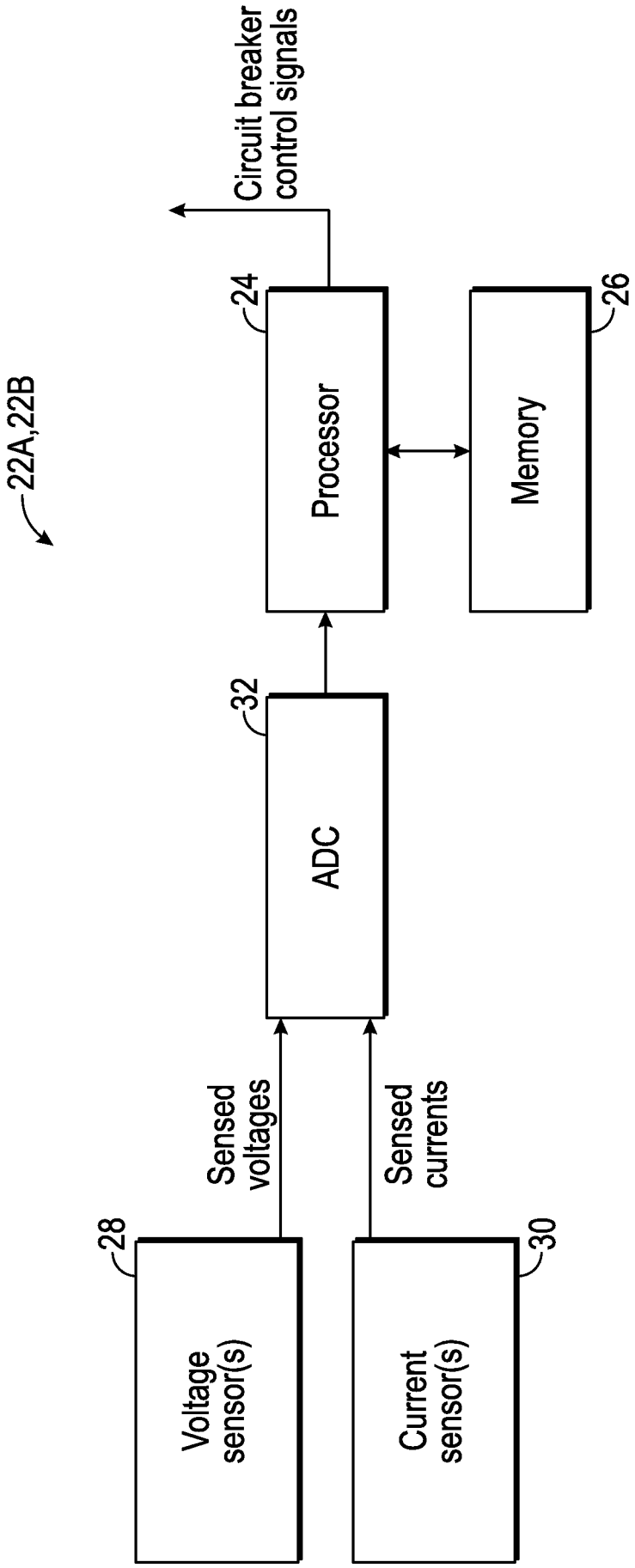

22A,22B
Circuit breaker control signals
24
Processor
26
Memory
32
ADC
Sensed voltages
Sensed currents
28
Voltage sensor(s)
30
Current sensor(s)

FIG. 2

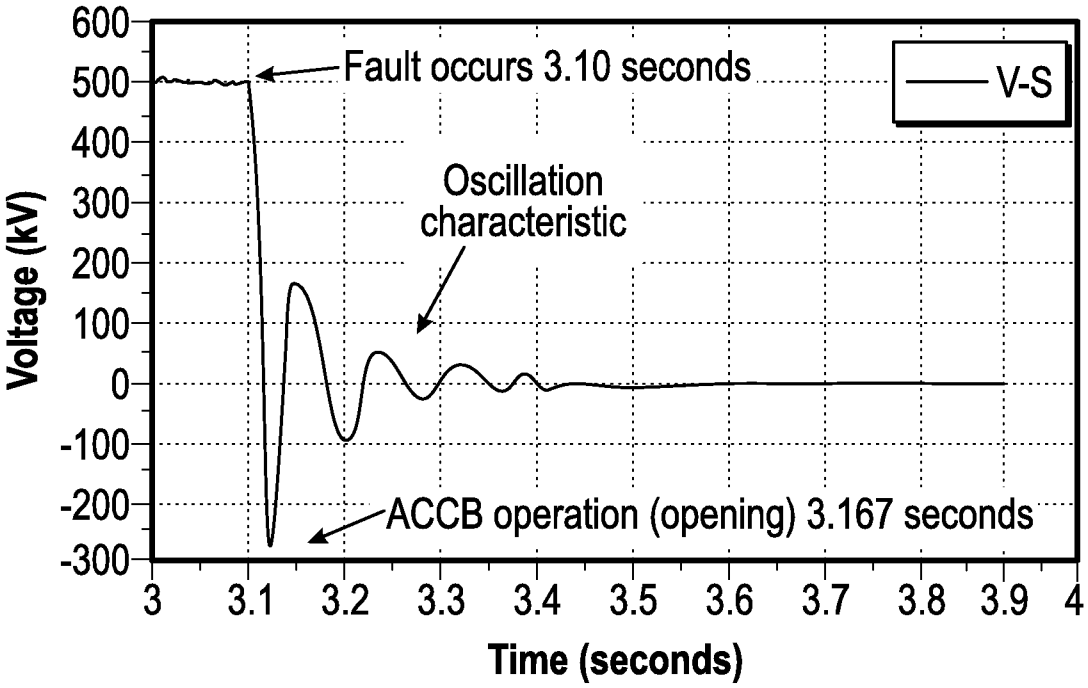

600
500
400
300
200
100
0
-100
-200
-300
Voltage (kV)
Fault occurs 3.10 seconds
V-S
Oscillation characteristic
ACCB operation (opening) 3.167 seconds
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4
Time (seconds)

FIG. 3

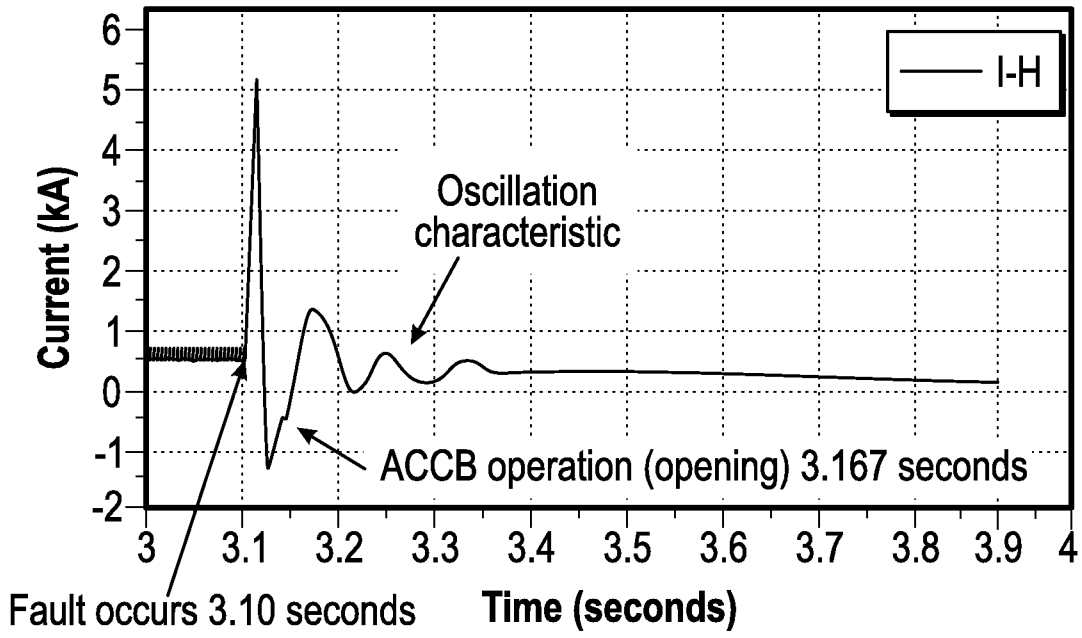

6
5
4
3
2
1
0
-1
-2
Current (kA)
I-H
Oscillation characteristic
ACCB operation (opening) 3.167 seconds
3
3.1
3.2
3.3
3.4
3.5
3.6
3.7
3.8
3.9
4
Fault occurs 3.10 seconds
Time (seconds)

FIG. 4

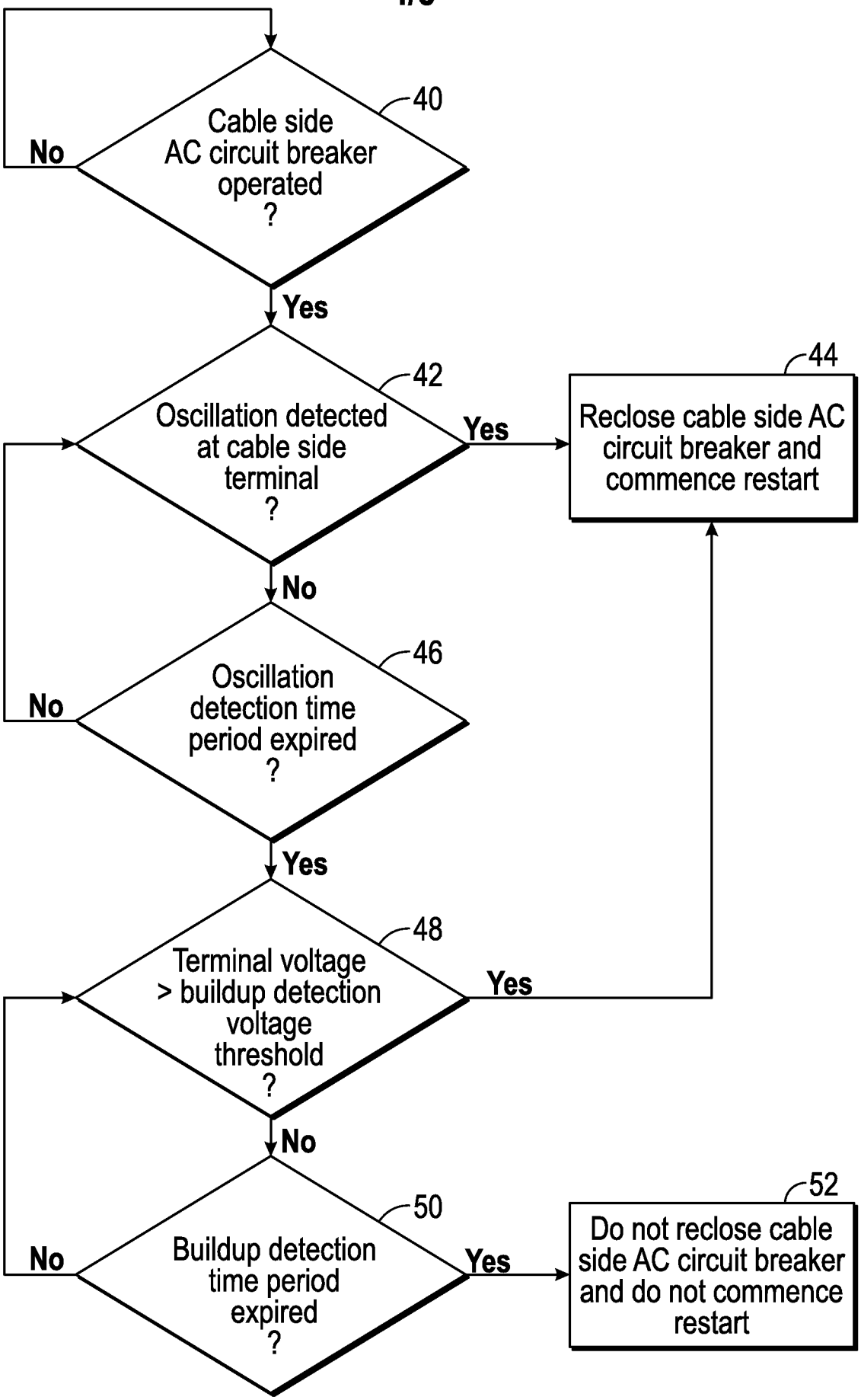

Cable side AC circuit breaker operated ?
40
No
Yes
Oscillation detected at cable side terminal ?
42
Yes
Reclose cable side AC circuit breaker and commence restart
44
No
Oscillation detection time period expired ?
46
No
Yes
Terminal voltage > buildup detection voltage threshold ?
48
Yes
No
Buildup detection time period expired ?
50
No
Yes
Do not reclose cable side AC circuit breaker and do not commence restart
52

FIG. 5

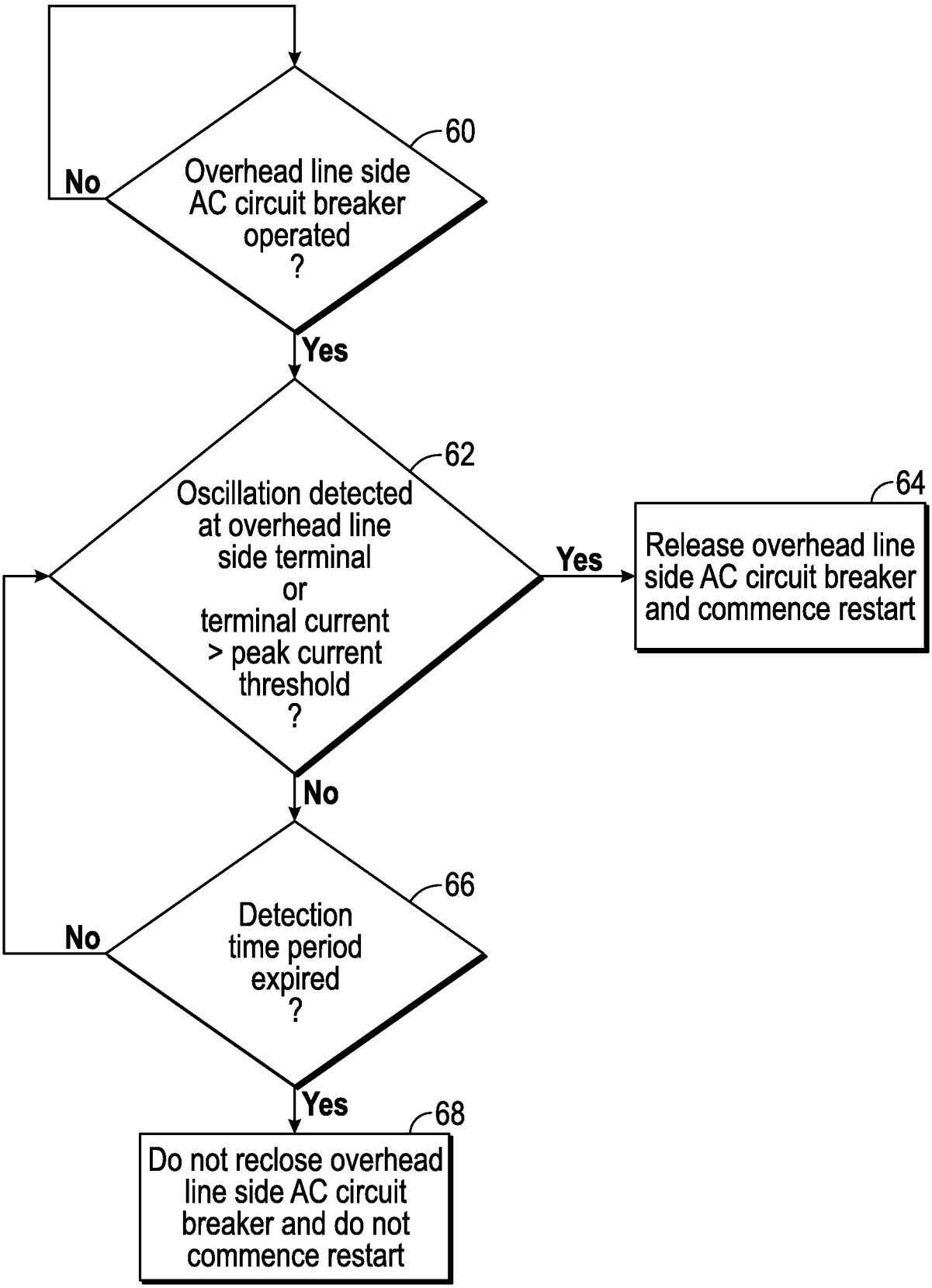

60
Overhead line side AC circuit breaker operated ?
No
Yes
62
Oscillation detected at overhead line side terminal or terminal current > peak current threshold ?
Yes
64
Release overhead line side AC circuit breaker and commence restart
No
66
Detection time period expired ?
No
Yes
68
Do not reclose overhead line side AC circuit breaker and do not commence restart

FIG. 6

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/033218

A. CLASSIFICATION OF SUBJECT MATTER

G01R 31/08(2006.01)I, H02H 7/26(2006.01)I

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G01R 31/08; H02H 3/42; G01R 31/11; H02H 7/26; H01H 33/16; H02H 9/00

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
Korean utility models and applications for utility models
Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
eKOMPASS(KIPO internal) & Keywords: hybrid voltage direct current, fault, overhead section, cable section, characteristic voltage oscillation

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	WO 2015-070942 A1 (ABB TECHNOLOGY AG) 21 May 2015 See page 5, lines 1-2; claim 1; and figure 1.	1-3,9-11,18-20,25-27
Y	US 2013-0088802 A1 (BERGGREN et al.) 11 April 2013 See paragraph [0066]; claim 10; and figure 2.	1-3,9-11,18-20,25-27
A	WO 2013-071974 A1 (ABB RESEARCH LTD.) 23 May 2013 See figure 1.	1-3,9-11,18-20,25-27
A	US 2012-0234796 A1 (JUHLIN) 20 September 2012 See figure 6.	1-3,9-11,18-20,25-27
A	US 2008-0158756 A1 (LINDSEY et al.) 03 July 2008 See figure 2.	1-3,9-11,18-20,25-27

☐ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents,such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 September 2016 (02.09.2016)	**05 September 2016 (05.09.2016)**

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INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2016/033218

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☒ Claims Nos.: 5, 13, 31
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:
Claims 5, 13, and 31 are not clear because they refer to claims 4, 12, and 30 respectively, which do not comply with PCT Rule 6.4(a).

3. ☒ Claims Nos.: 4, 6-8, 12, 14-17, 21-24, 28-30, 32
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required addtional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☐ As all searchable claims could be searched without effort justifying an additional fees, this Authority did not invite payment of any additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
☐ No protest accompanied the payment of additional search fees.

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2016/033218

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 2015-070942 A1	21/05/2015	EP 2873982 A1	20/05/2015
		EP 2873982 B1	27/04/2016
US 2013-0088802 A1	11/04/2013	CN 103004048 A	27/03/2013
		CN 103004048 B	15/04/2015
		EP 2580828 A1	17/04/2013
		US 8749933 B2	10/06/2014
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WO 2013-071974 A1	23/05/2013	EP 2780998 A1	24/09/2014
		EP 2780998 B1	11/05/2016
US 2012-0234796 A1	20/09/2012	CN 102656656 A	05/09/2012
		CN 102656656 B	11/03/2015
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		EP 2494571 B1	11/12/2013
		KR 10-1342333 B1	16/12/2013
		KR 10-2012-0079156 A	11/07/2012
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		WO 2008-088448 A1	24/07/2008